AD-A273 621

...ITATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
August 1993

3. REPORT TYPE AND DATES COVERED
Professional Paper

4. TITLE AND SUBTITLE
STOCHASTIC RESONANCE IN A BISTABLE SQUID LOOP

5. FUNDING NUMBERS
PR: MA19
PE:
WU:

6. AUTHOR(S)
A. Hibbs, E. W. Jacobs, J. Bekkedahl, A. Bulsara

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Command, Control and Ocean Surveillance Center (NCCOSC)
RDT&E Division
San Diego, CA 92152-5001

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Stochastic Resonance (SR) is the name given to a statistical nonlinear phenomenon whereby a weak or subthreshold coherent function can be amplified by random forces, or noise, within the system. It was first advanced in the early 1980's as a possible explanation for the observed periodicities in the recurrences of the Earth's Ice Ages. The first publication of a modern theory led to an experiment and a flurry of further theoretical activity, an international conference and a review. In this paper, we describe a demonstration experiment wherein SR is exhibited in a superconducting quantum interference device (SQUID). Here SR is viewed as a noisy information transmission process. It is entirely appropriate, therefore, to look for this dynamic in a widely used sensitive detector; in this example, a detector of weak magnetic fields. Using a modern, miniature, thin film SQUID, we hope this demonstration will stimulate further research and development of SR in applied superconductivity.

Published in *Noise in Physical Systems & 1/F Fluctuations*, AIP 285, 1993, pp. 720-723.

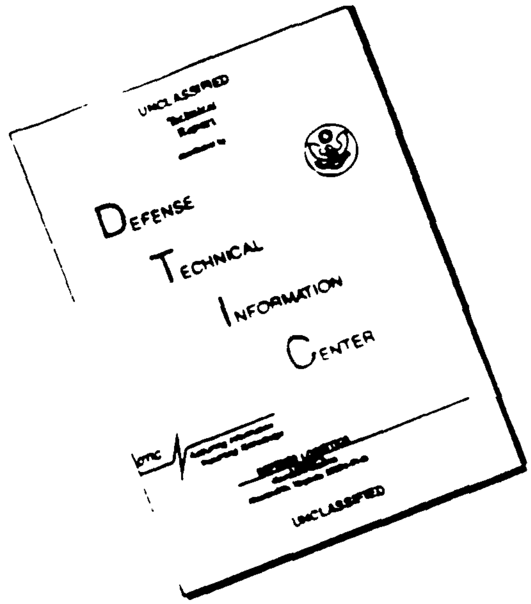
14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAME AS REPORT

DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

21a NAME OF RESPONSIBLE INDIVIDUAL	21b TELEPHONE (Include Area Code)	21c OFFICE SYMBOL
A. R. Bulsara	(619) 553-1595	Code 573

93-29770

\`ePG

93 12 6 097

NSN 7540-01-280-5500

Standard form 298 (BACK)

UNCLASSIFIED

STOCHASTIC RESONANCE IN A BISTABLE SQUID LOOP

A. Hibbs
Quantum Magnetics, Inc., San Diego, CA, USA

E. W. Jacobs, J. Bekkedahl, A. Bulsara
Navy Command, Control and Ocean Surveilance Center, San Diego, CA, USA

F. Moss
University of Missouri at St. Louis, MO, USA

ABSTRACT

Stochastic Resonance (SR) is the name given to a statistical nonlinear phenomenon whereby a weak or subthreshold coherent function can be amplified by random forces, or noise, within the system. It was first advanced in the early 1980's as a possible explanation for the observed periodicities in the recurrences of the Earth's Ice Ages[1,2]. The first publication of a modern theory[3-5] led to an experiment[4] and a flurry of further theoretical activity[6-9], an international conference[10] and a review[11]. In this paper, we describe a demonstration experiment wherein SR is exhibited in a superconducting quantum interference device (SQUID). Here SR is viewed as a noisy information transmission process. It is entirely appropriate, therefore, to look for this dynamics in a widely used sensitive detector in this example, a detector of weak magnetic fields. Using a modern, minature, thin film SQUID[12], we hope this demonstration will stimulate further research and development of SR in *applied superconductivity*.

INTRODUCTION

We have demonstrated *Stochastic Resonance*[1] in a bistable SQUID loop, as a first step in stimulating interest in possible applications using superconducting devices. We begin with an equation governing the magnetic flux trapped within an rf SQUID loop[13]

$$LC\ddot{\varphi} + \tau_L\dot{\varphi} + \varphi + \frac{1}{2\pi}\beta\sin(2\pi\varphi) = \varphi_e , \tag{1}$$

where $\varphi = \Phi(t)/\Phi_0$ is the normalized magnetic flux trapped within the loop, $\varphi_e = \Phi_e(t)/\Phi_0$ is the normalized flux externally imposed on the loop, $\Phi_0 \cong h/2e$ is the flux quantum, L and C are the loop inductance and junction capacitance respectively, and $\tau_L = L/R_J$ is the junction resistance. The parameter which determines the shape of the potential governing the dynamics of (1) is $\beta = 2\pi L i_c/\Phi_0$, where i_c is the junction critical current. In our experiment, the external flux Φ_e was composed of DC, periodic and stochastic components

$$\Phi_e(t) = \Phi_{DC} + \Phi_{ac}\sin(\omega_s t) + \Phi_N(t), \tag{2}$$

where the periodic component represents an audio frequency signal, and the stochastic component was a Gaussian noise whose bandwidth was in the audio range[14]. Bistability is a prerequisite for observations of SR. Equation (1) is bistable for certain values of β and Φ_{DC}, and the quantity which shows the bistable dynamics is the flux trapped within the loop, $\varphi(t)$.

DESCRIPTION OF THE EXPERIMENTAL APPARATUS

In order to experimentally observe the bistable dynamics, one must measure the trapped flux $\phi(t)$. This requires a second SQUID, either mounted coaxially with the loop of the first SQUID, or coupled to it with a superconducting transformer[15]. We chose the latter configuration. The primary SQUID was a thin film device mounted on a single chip with integrally mounted, superconducting transformer primaries supplied by Quantum Magnetics. This is a thin film SQUID with primary and secondary windings coupled to the SQUID all evaporated on a single silicon chip. The Quantum Design DC SQUID chip is shown in Fig. 1. It is the first commercially available and the most sensitive all-thin-film DC SQUID sensor. The junctions, located in the central region ot the chip, are made in the state-of-the-art niobium trilayer technology on silicon and are part of two two identical loops connected in parallel, each coupled to an input coil. This unique "double balanced" design reduces coupling between the input and modulation

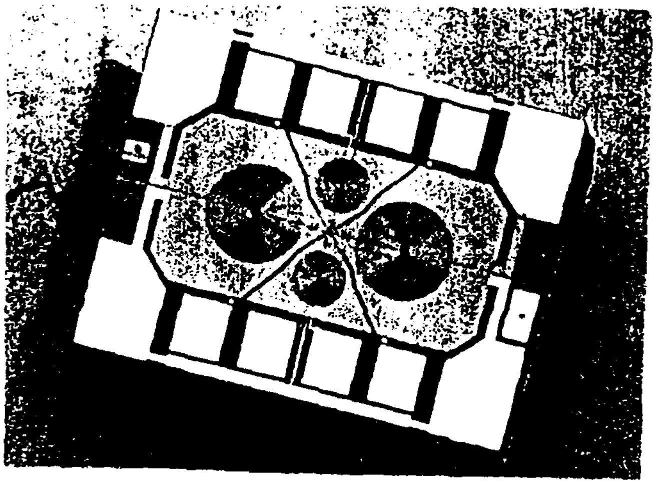


Fig. 1. The Quantum Design DC SQUID. The rectangles around the edges are bond pads for electrical connections. The left and right spiral coils couple the input signal to the SQUID loops. The upper and lower coils are used for a 500 kHz AC flux modulation used for noise reduction. The current and voltage leads appear as a cross but are not connected in the middle. The two Josephson junctions are located at the lower left and upper right of the cross but near the center. The size of the chip shown is 5 *x* 3 mm.

coils to negligible levels while giving high mutual inductance with the SQUID.

The secondary, or measuring, SQUID was a standard BTI model[16], which was coupled to the primary SQUID with a completely superconducting transformer. A schematic diagram of the experimental setup is shown in Fig. 2. This apparatus was mounted inside a superconducting *Nb* shield and mounted near the bottom of a liquid helium dewar. The apparatus was operated at a temperature of 4.2 ^{0}K in boiling liquid helium. No further external magnetic shielding was employed.

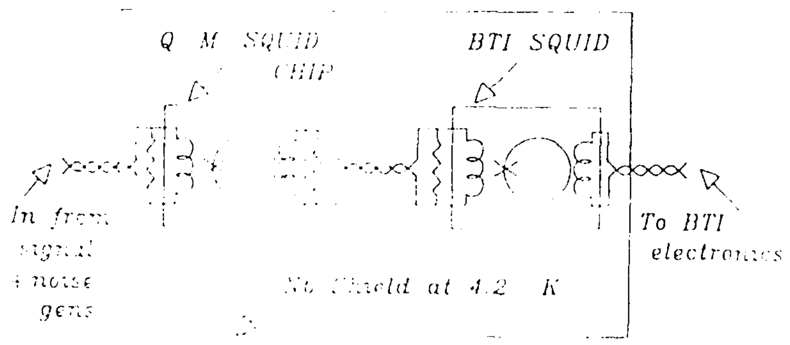


Fig. 2. Schematic of the bistable SQUID experiment showing the Quantum Magnetics chip and the BTI measuring SQUID coupled with a superconducting transformer. Noise and signal voltages supplied by the external electronics were transformed into external magnetic flux in the coil C1.

EXAMPLE EXPERIMENTAL RESULTS

In our experiment, $\beta = 2.0$ and $\Phi_{DC} = 0.5\Phi_0$, values which guaranteed that the potential was bistable. Experiments were performed at two signal frequencies, 17.6 *Hz* and 100 Hz with signal peak voltages of 650 *mV-pk* and 475 *mV-pk* respectively. The *noise, or stochastic, component* was supplied by a *standard noise* generator and the noise voltage varied over the range from 100 to 1500 *mV*-rms. (1.0 *V* was equivalent to $0.1\Phi_0$ of applied external flux.) The power spectra of $\phi(t)$ were measured and averaged in the usual way at the output of the BTI SQUID electronics, and the signal-to-noise ratios (SNR's) were determined from the measured and time averaged power spectra of the output of the BTI electronics using a conventional definition. The results of this experiment are shown in Fig. 3 where the circles represent the results for the low signal frequency and the squares for the high frequency.

At each frequency, data were collected for two different signal strengths. For each data set, a clear maximum in the SNR - the familiar signature of SR - was observed. The maxima in the SNR occur at a noise voltage of ≈ 700 *mV* which is equivalent to an rms fluctuation of $0.07\Phi_0$ within which a coherent signal equivalent to $0.0237\Phi_0$ peak at 17.6 Hz was easily detectable. This clearly demonstrates that bistable SQUIDs, used in combination with SR, can be useful in detecting weak, coherent magnetic signals buried in external noise, an application of considerable importance.

Work supported by the U.S. Office of Naval Research grant N00014-91-J-1979 and by Quantum Magnetics, Inc.

REFERENCES

1. R. Benzi, S. Sutera and A. Vulpiani, J. Phys. A 14, L453 (1981).
2. C. Nicolis, Tellus 34, 1 (1982).
3. B. McNamara and K. Wiesenfeld, Phys. Rev. A 39, 4148 (1989).
4. B. McNamara, K. Wiesenfeld and R. Roy, Phys. Rev. Lett. 60, 2626 (1988).
5. P. Jung and P. Hanggi, Europhys. Lett 8, 505 (1989).

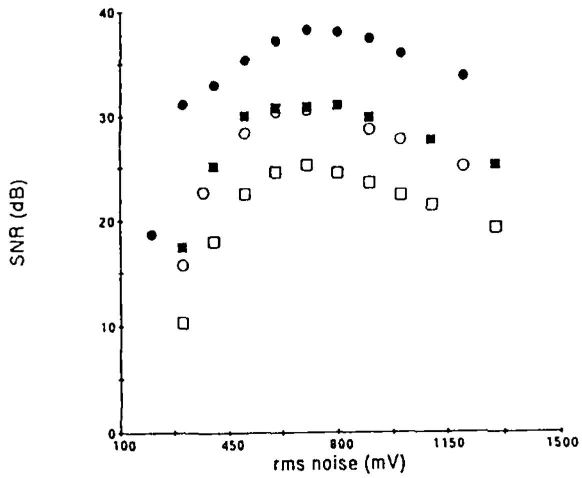


Fig. 3. The SNR versus rms noise voltage for the bistable SQUID experiment, with f_s = 17.6 Hz, v_s = 650 mV-rms (filled circles) and v_s = 237 mV (open circles); and f_s = 100 Hz, v_s = 475 mV (filled squares) and v_s = 237 mV (open squares). For these data 1.0 $V \equiv 0.1\Phi_0$ at the coil C1.

6. L. Gammaitoni, F. Marchesoni, E. Menichella-Saetta, and S. Santucci, Phys. Rev. Lett. 62, 349 (1989)
7. P. Jung, Z. Phys. *B* 16, *521 (1989)*
8. P. Jung and P. Hanggi, Phys. Rev. A 41, 2977 (1990)
9. M. Dykman, R. Mannella, P. McClintock, and N. Stocks, Phys. Rev. Lett. 65, 2606 (1990)
10. *Proceedings of the N.A.T.O. Advanced Research Workshop on Stochastic Resonance in Physics and Biology*, edited by F. Moss, A. Bulsara and M. F. Shlesinger, special issue, J. Stat. Phys. 70 (1993).
11. F. Moss, "Stochastic Resonance: from the Ice Ages to the Monkey's Ear" in *An Introduction to Some Contemporary Problems in Statistical Physics*, edited by George H. Weiss (SIAM, Philadelphia, in press).
12. Quantum Magnetics, 11578 Sorrento Valley Road, Suite 30; San Diego, CA 92121.
13. See for example, A. Barone and G. Paterno, *Physics and Applications of the Josephson Effect*, (John Wiley & Sons, Inc., New York, NY, 1982).
14. *rf*-SQUIDS can respond in the frequency range from DC to gigahertz, and the external electronics in our experiment had a bandwidth to 30 kHz, consequently the SQUID and its external electronics can respond essentially instantaneously to both the signal and the noise.
15. A. Silver and J. Zimmerman, Phys. Rev. 157, 317 (1967)
16. Biomagnetic Technologies Inc.; San Diego, CA; Model 420.